

# Beam Physics at UCLA-ATF Pulse Compression Experiment

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RadiaBeam Technologies, LLC  
(and UCLA Particle Beam Physics Laboratory)

# Collaboration

## ✓ UCLA

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## ✓ BNL-ATF

- M. Babzien, I. Ben-Zvi, K. Kusche, R. Malone, M. Woodle, V. Yakimenko

## ✓ INFN-LNF

- G. Palumbo, C. Vicario

## ✓ Univ. Milano

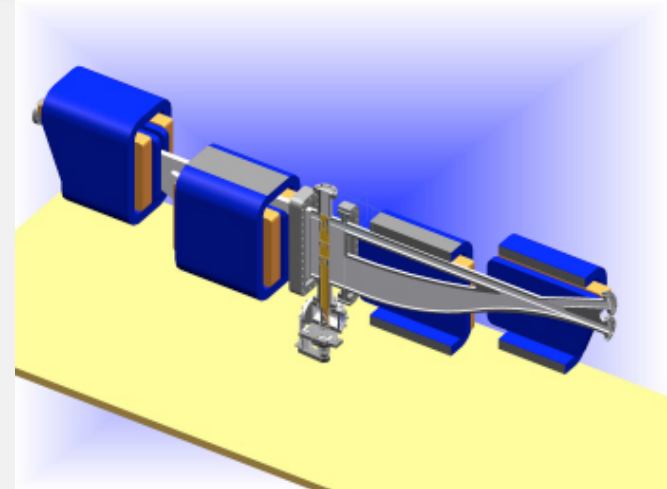
- A. Flacco

# Outline

- ✓ Motivation for chicane compressor studies
  - applications for sub-picosecond beams
  - limitations of the simple compression model
- ✓ ATF compressor design and installation
  - magnets and vacuum chamber
  - e-beam diagnostics
  - commissioning
- ✓ Coherent Radiation Studies
  - CER (Coherent Edge Radiation)
  - bunch length measurements with CTR
- ✓ Initial Results
- ✓ Outlook

# Compressor

- ✓ Designed and Constructed at UCLA
  - R. Agustsson master thesis
  - Modeled with Amperes
  - Some engineering + safety concerns addressed by ATF
- ✓ Installed and operational at ATF
  - Installation work started in 2003
  - Experimental studies in progress, initial results obtained.
- ✓ Extensive Simulation work
  - TREDI, Field-Eye, Parmela, Elegant





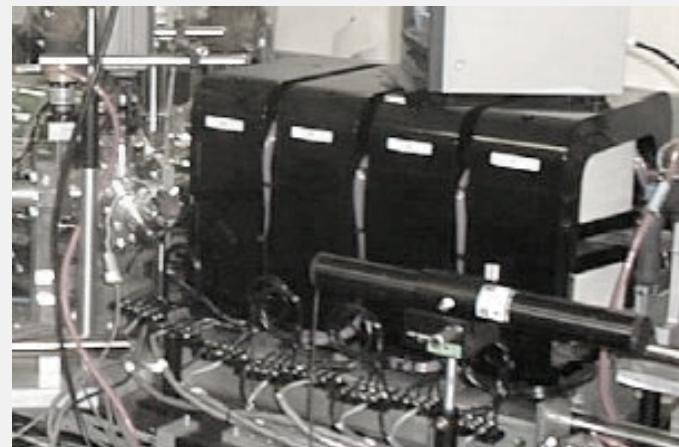
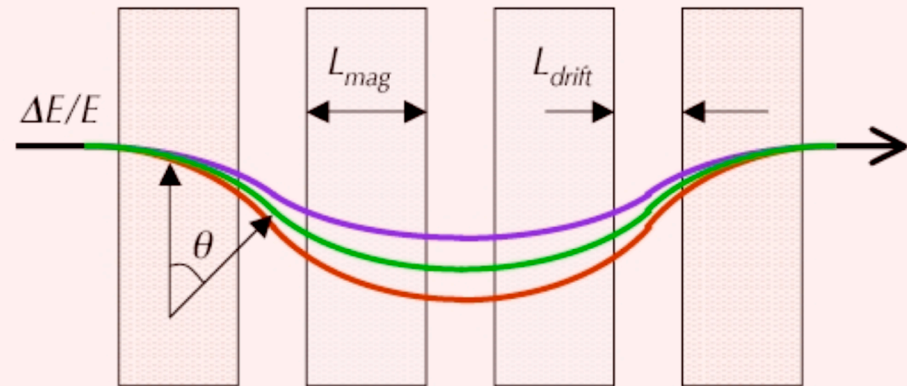
# Magnetic Bunch Compression

In the chicane larger energy particles move along the shorter trajectory. When the bunch is properly chirped in the linac before the chicane entrance (so that the more energetic particles are in the tail of the bunch) an overall bunch compression can be achieved.

$$\Delta L = R_{56} \frac{\Delta E}{E} + T_{566} \left( \frac{\Delta E}{E} \right)^2$$

The linear term is defined by the geometry of the magnets:

$$R_{56} = 2\theta^2(L_{dft} + \frac{2}{3}L_{mag})$$



# Motivation for Shorter Bunches

## ✓ Advanced Acceleration Schemes

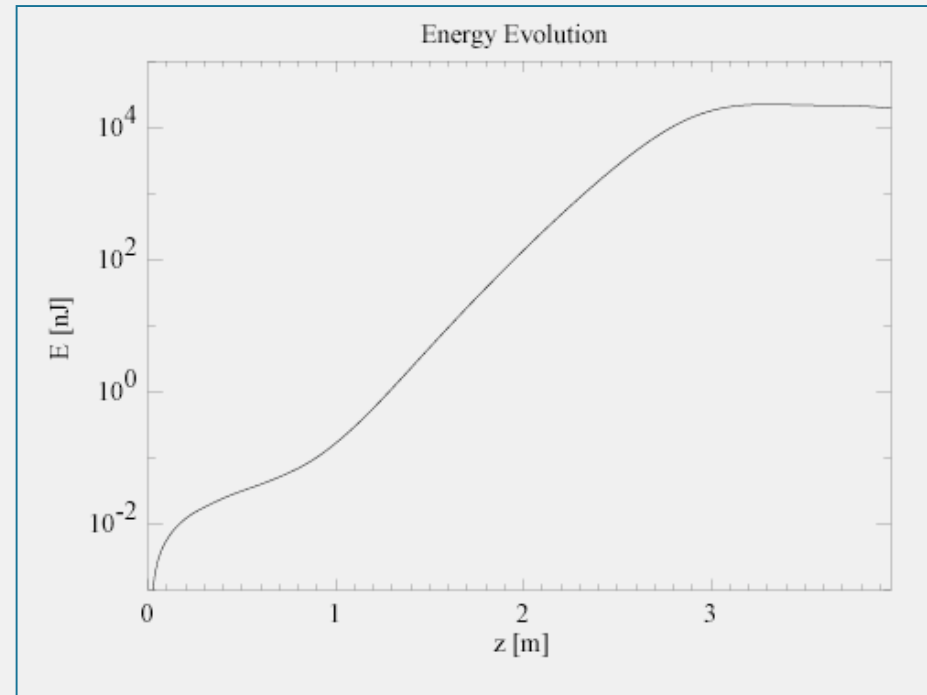
- Plasma-Beam Interactions
- Laser-Beam Interactions
- Wakefield Accelerators

## ✓ Light Sources

- Free Electron Lasers
- Inverse Compton Scattering

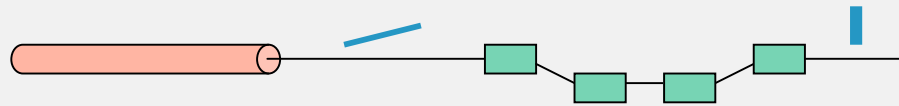
VISA example:  
running chicane would allow  
saturation in less than 3 m.

$$I_p \sim 1.3 \text{ A}$$



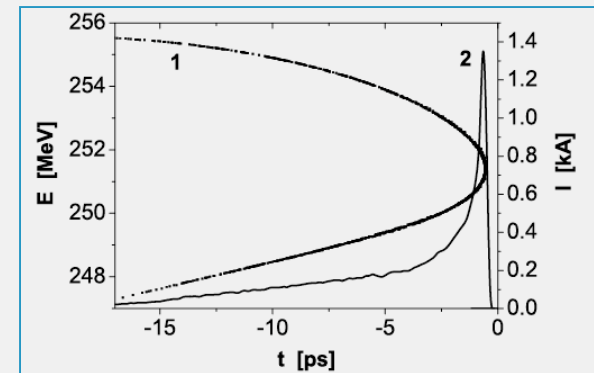
# Limits of Magnetic Compression

In the ideal world, one can start with the linear chirp, and obtain a perfectly compressed beam, limited only by the uncorrelated energy spread :



Other limiting factors need to be considered:

- ✓ nonlinearities in the e-beam longitudinal phase space before after the linac
  - non-linear curvature
  - space charge induced energy modulation
  - non-flat current distribution
- ✓ chicane imperfections
  - asymmetries and 2-nd order transport elements
- ✓ collective effects
  - CSR (Coherent Synchrotron Radiation)
  - space charge effect
  - wakefields



# Goals of UCLA/ATF Program

- ✓ Enhance the ATF capabilities to allow high peak current experiments.
- ✓ Comprehensive studies of the beam physics in the chicane:
  - Beam compression efficiency studies;
  - Emittance growth in chicane;
  - Transverse phase space evolution;
- ✓ Collective effects
  - CER spectrum characterization;
- ✓ Development of numerical methods
  - Start-to-end simulations using PARMELA-ELEGANT;
  - New code development to include collective effects;

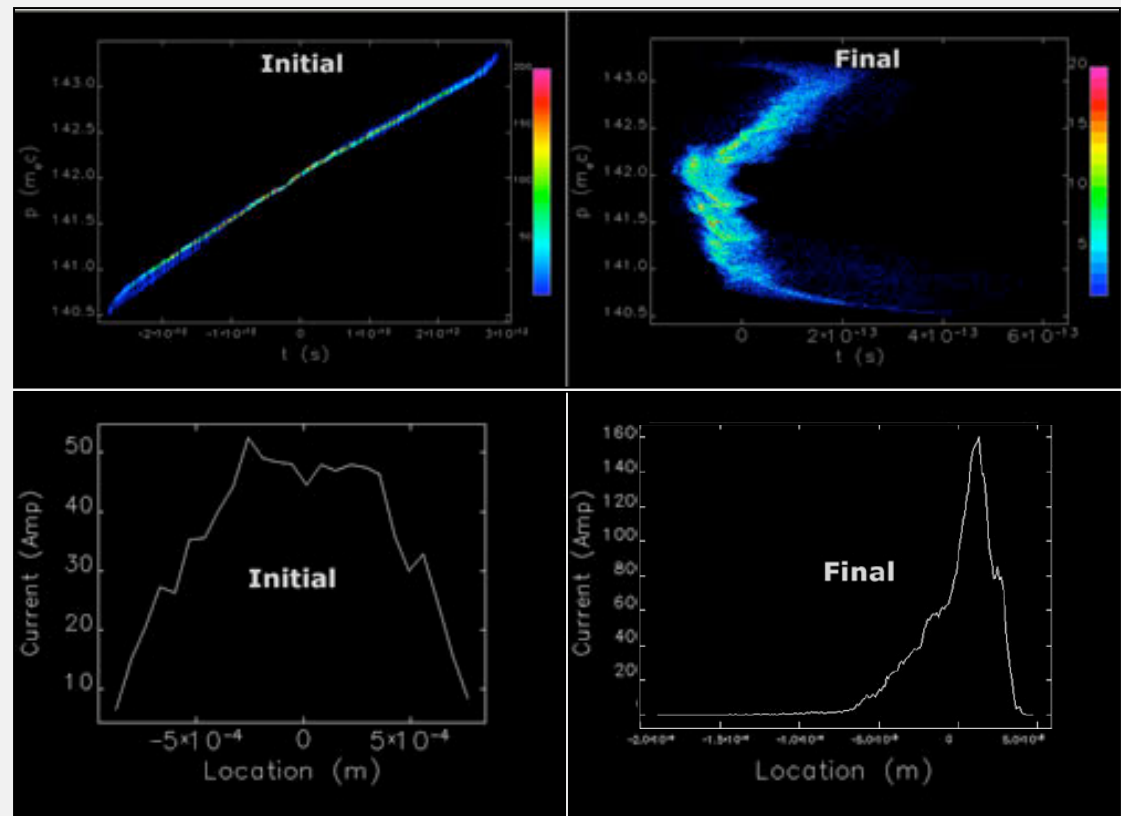
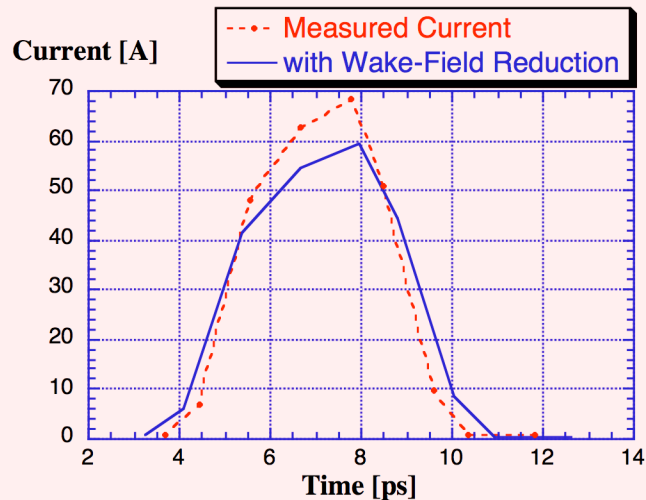
# Design Parameters

## ✓ PARMELA - ELEGANT Simulations

### Beam Parameters:

$\mathcal{E} \sim 72 \text{ MeV}$      $Q \sim 200 \text{ pC}$

$\varepsilon_n \sim 1.5 \text{ } \mu\text{m}$      $I_p \sim 55 \text{ A}$



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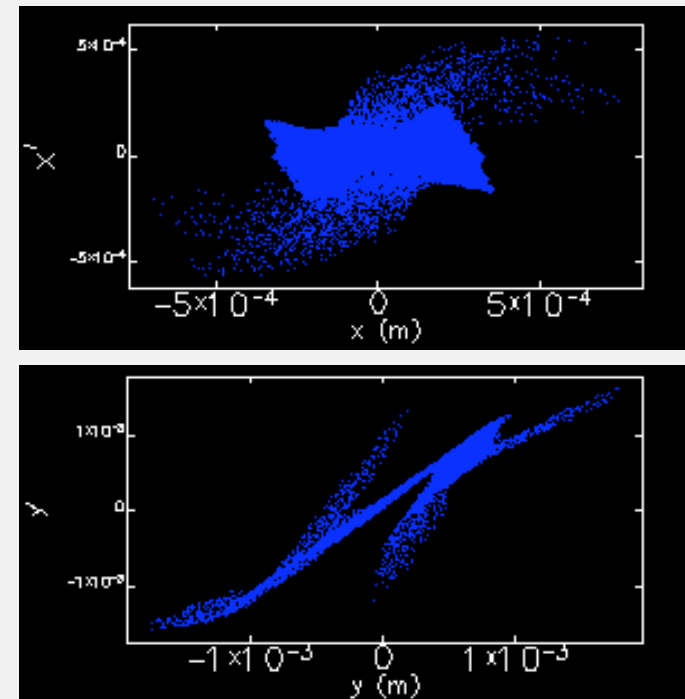
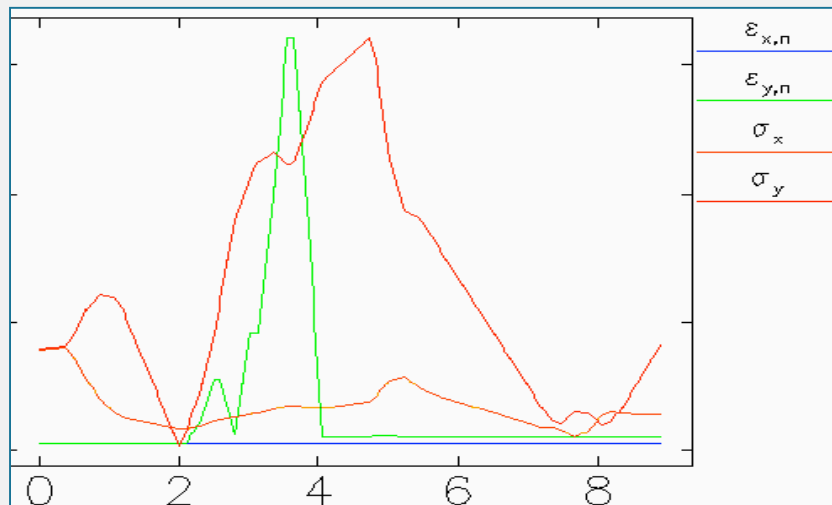
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# Emittance Growth

Two mechanisms of  $\epsilon_{y,n}$  growth:

- 2nd order effects due to large beam size
- CSR and space charge effects



Initial beam:  
 $\epsilon_{n,x} = \epsilon_{n,y} \sim 1.5 \mu\text{m}$



Final beam:

$\epsilon_{n,x} \sim 1.5 \mu\text{m}$  (no change)

$\epsilon_{n,y} \sim 3.1 \mu\text{m}$  (without CSR) and  $5.8 \mu\text{m}$  w/CSR

# Model Limitations

## ELEGANT CSR model limitations:

- No space charge (or near field, or velocity field) is included;
- No boundaries are included;
- CSR model is based on a “thin beam” limit:

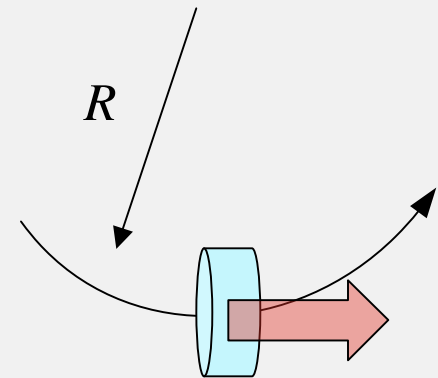
$$\sqrt{\frac{\sigma_y}{R}} \ll \frac{\sigma_z}{\sigma_y}$$

With the design parameters the Derbenev criterium is not satisfied:

$$\sigma_y \sim 1 \text{ mm}$$

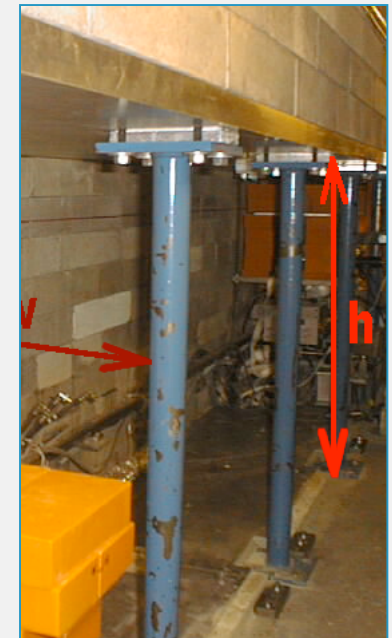
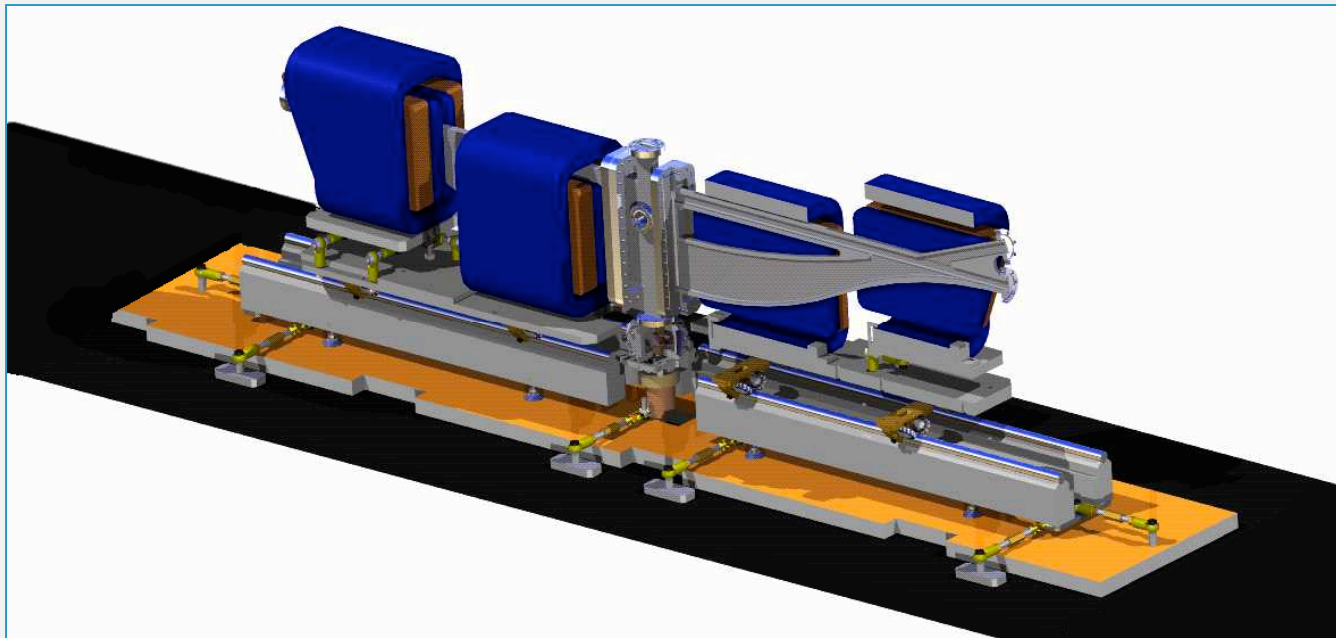
$$\sigma_z \sim 20 \text{ } \mu\text{m}$$

$$R = 1.2 \text{ m}$$



UCLA developed a new code, to directly calculate LW potentials.

# Engineering Design

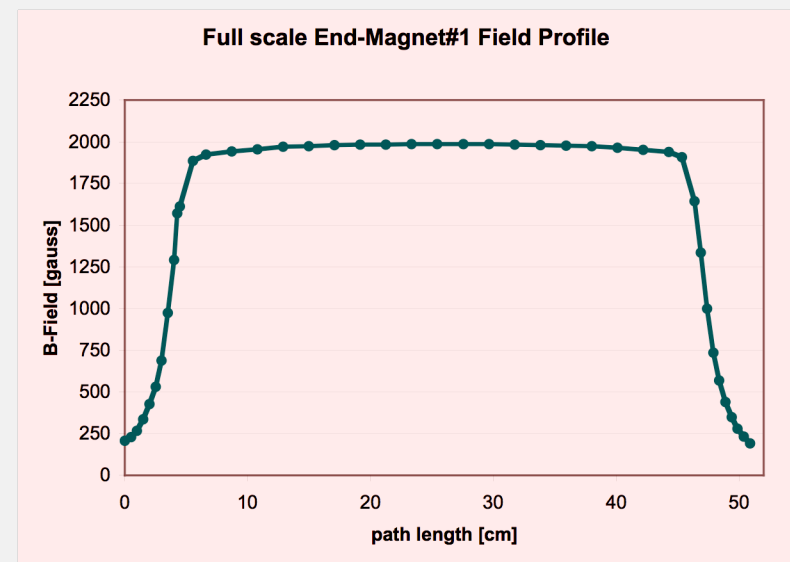
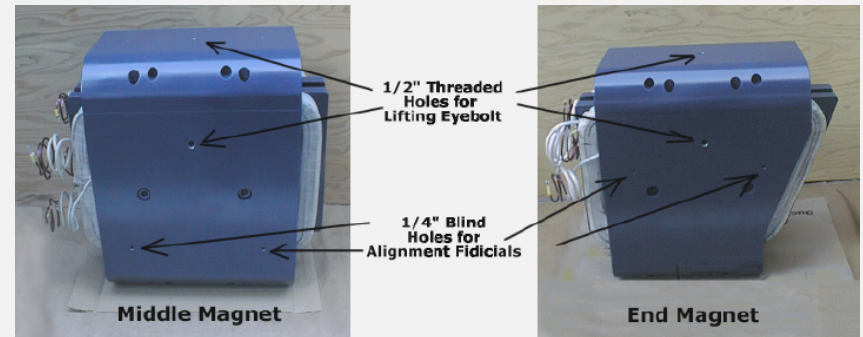
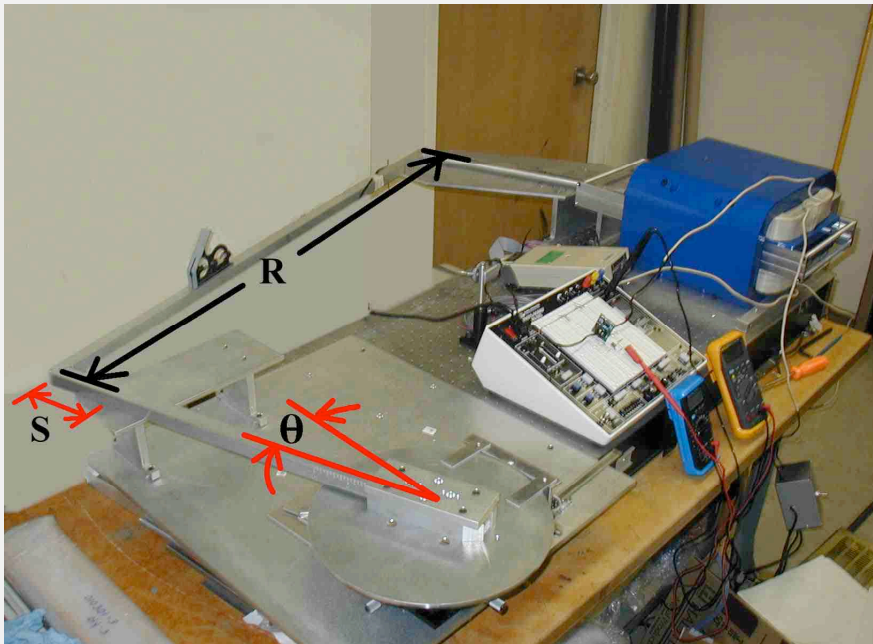


- ✓ System components: magnets, vacuum chamber, stand and rail system, centerpiece e-beam diagnostics, radiation port.

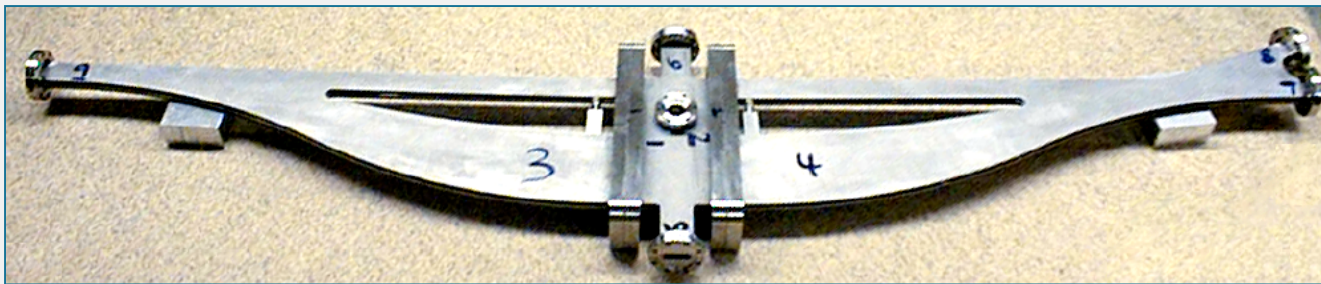
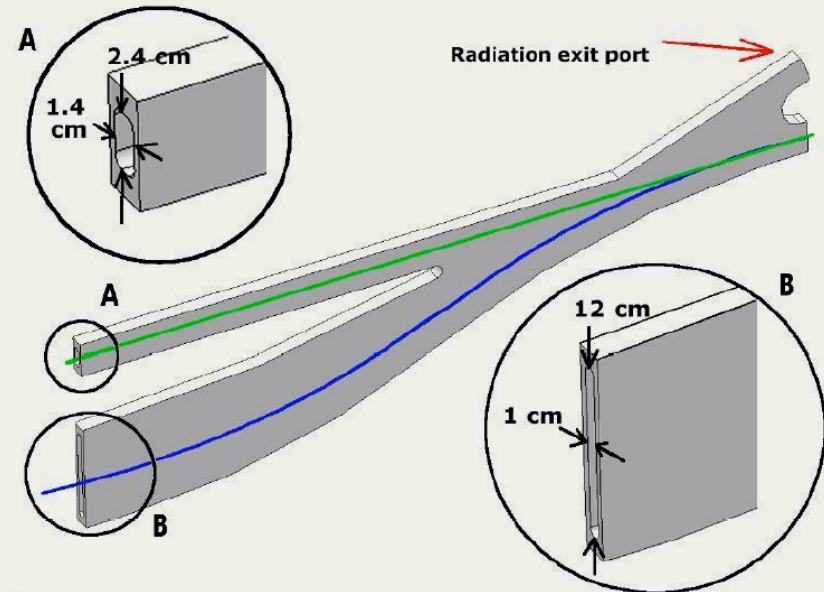


# Magnets

Magnet's edges provide for vertical focusing, while fringe fields provide for horizontal.



# Vacuum chamber and CER port



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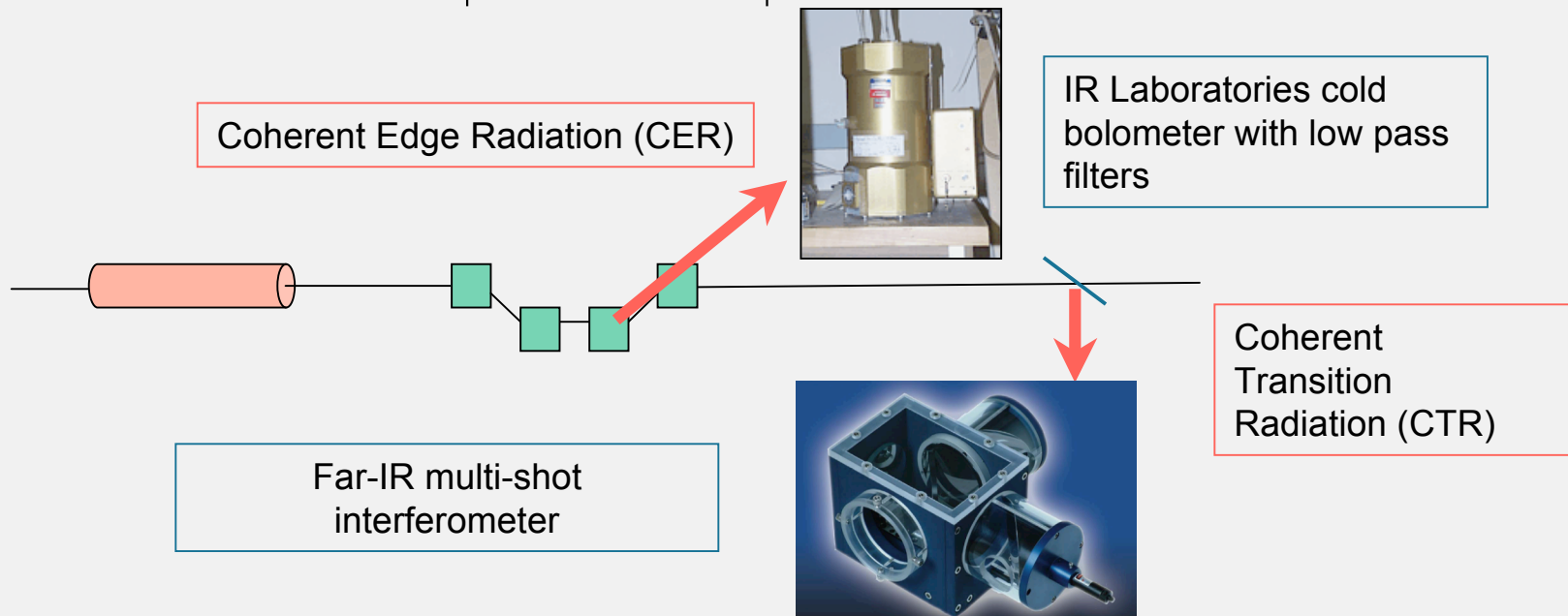
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# Coherent Radiation Measurements

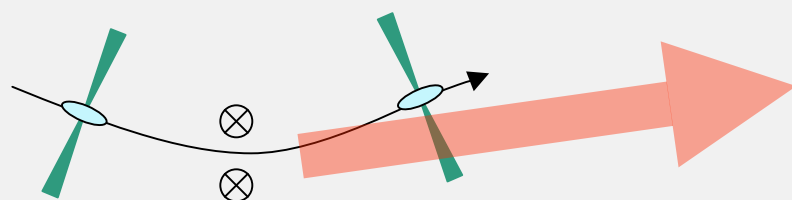
For an electron beam, the radiated spectral intensity depends on the longitudinal profile of the electron beam:

$$\mathcal{E}(\omega) \approx \mathcal{E}_0(\omega) N_e^2 \left| \frac{1}{Q} \int_{-\infty}^{\infty} I(t) e^{i\omega t} dt \right|^2 \sim \mathcal{E}_0(\omega) |\tilde{I}(\omega)|^2$$

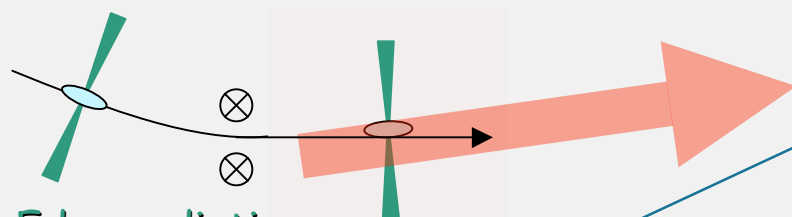


# Edge Radiation Spectrum

Edge radiation is a form of the synchrotron radiation while the beam crosses the boundary of a magnet.



Synchrotron radiation

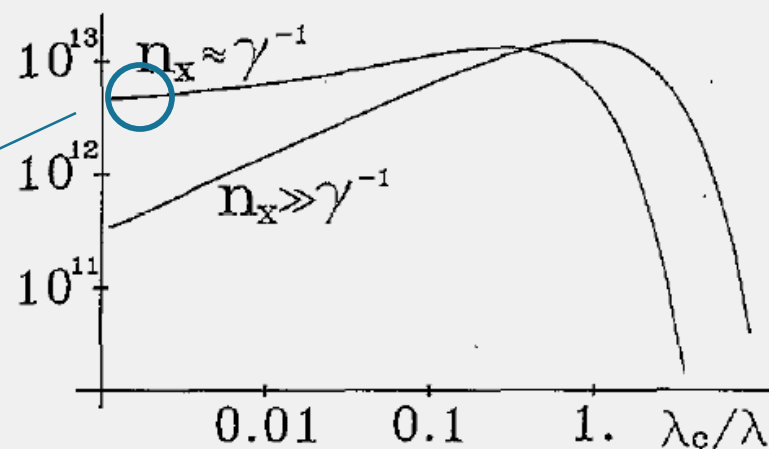


Edge radiation

$$\mathcal{E}(\omega) \sim |\tilde{I}(\omega)|^2$$

$$\mathcal{E}_0(\omega) \sim \omega^{2/3} \quad \left( \frac{c}{R} \ll \omega \ll \omega_c \right)$$

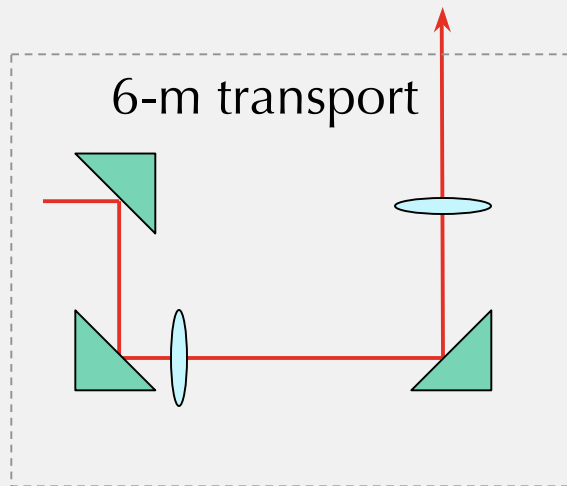
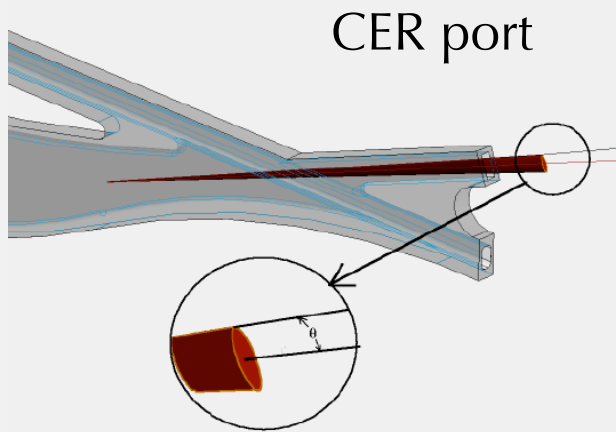
(peaked at  $\gamma\theta \sim 1$ )       $\lambda_c \sim 50 \text{ nm}$



O.V. Chubar, N.V. Smolyakov, J.Optics, **24**(3), 117 (1993)



# CER Measurements System



Cold filter wheel (low pass):  
(13, 27, 45, 103, 285  $\mu\text{m}$ )

Si bolometer  
at 4.2 K°

# First Results

- ✓ Chicane was turned on in Fall 2004
- ✓ Small vertical dispersion, full charge transmission
- ✓ Strong fragmentation of momentum distribution at 19° linac phase indicates compression

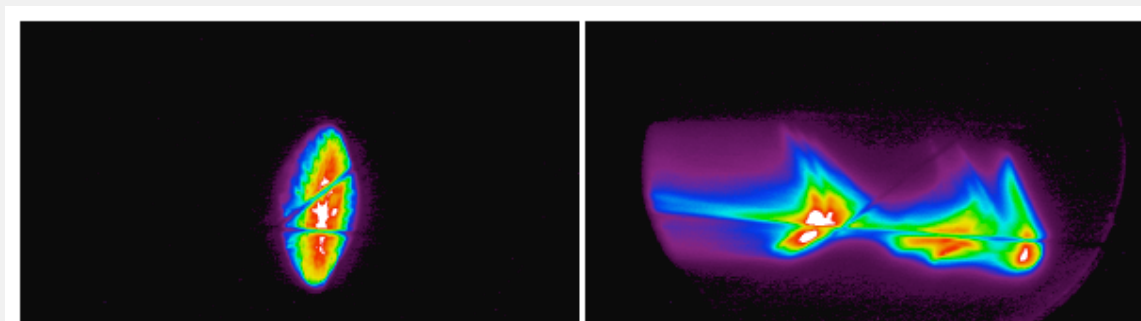
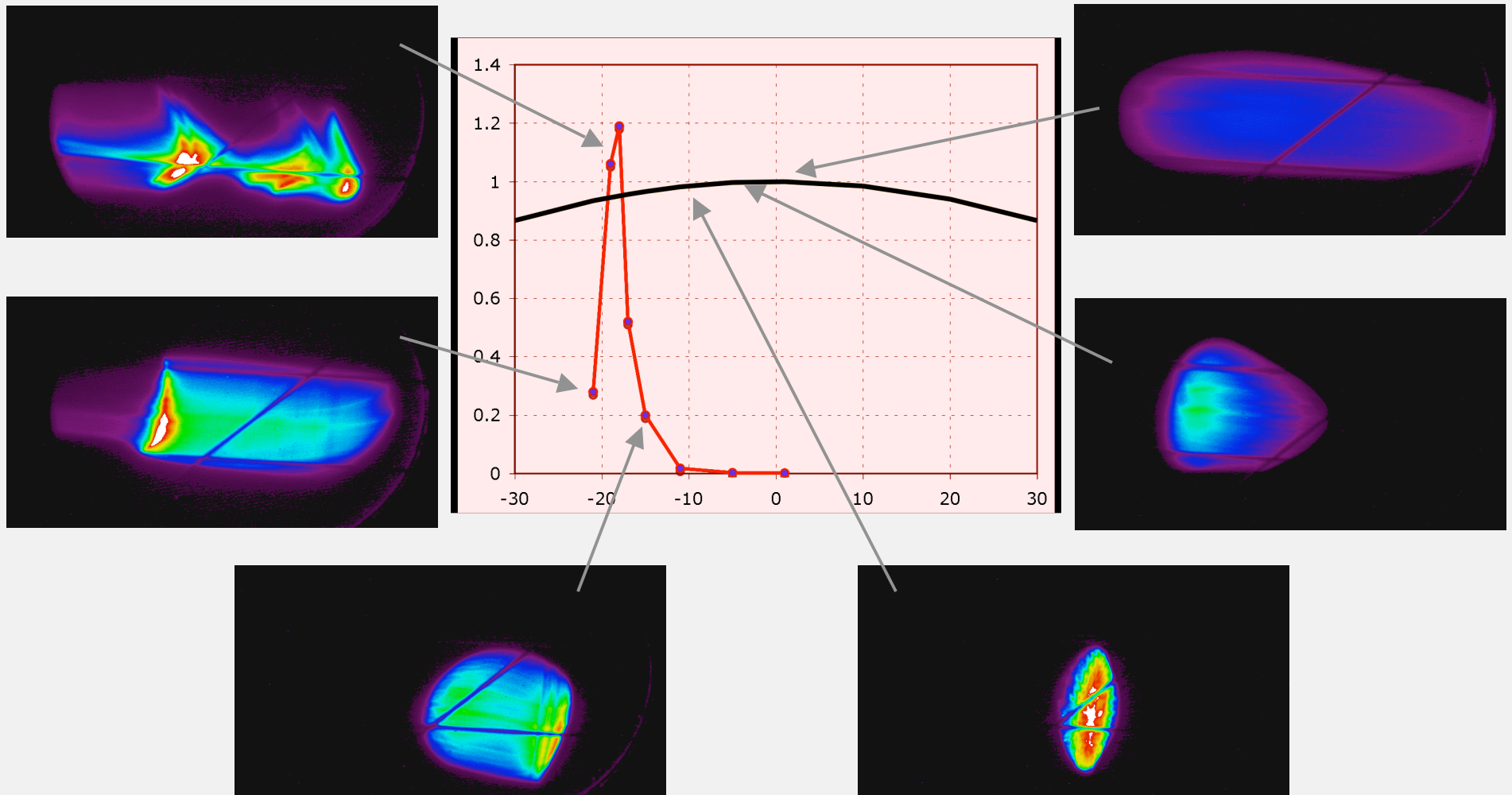


Image of beam in spectrometer (horizontal is bend plane).

Min. energy spread and no compression - 9 deg fwd of crest (left); Max. compression -19 deg fwd of crest (right).

# CER dependence on linac phase

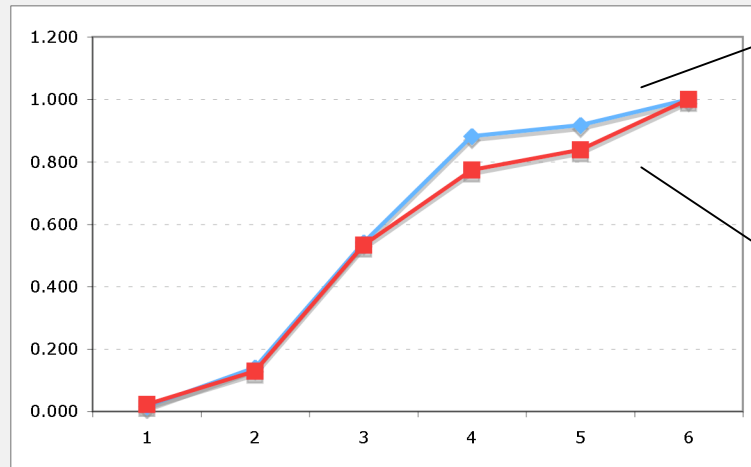


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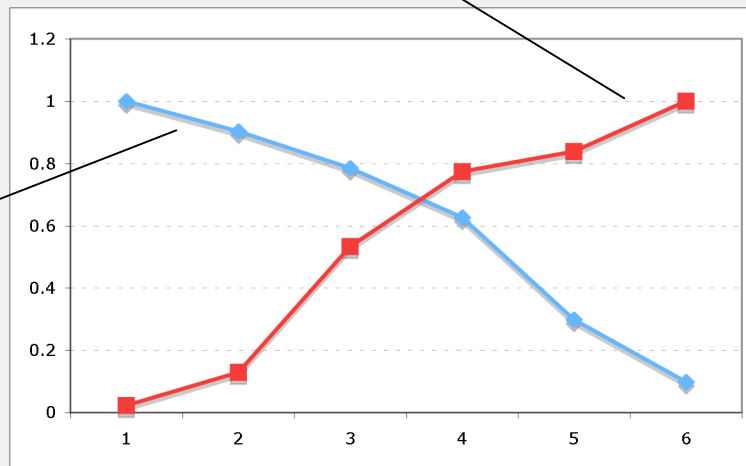
# CER Spectrum



minimum  $\Delta E/E$

compressed

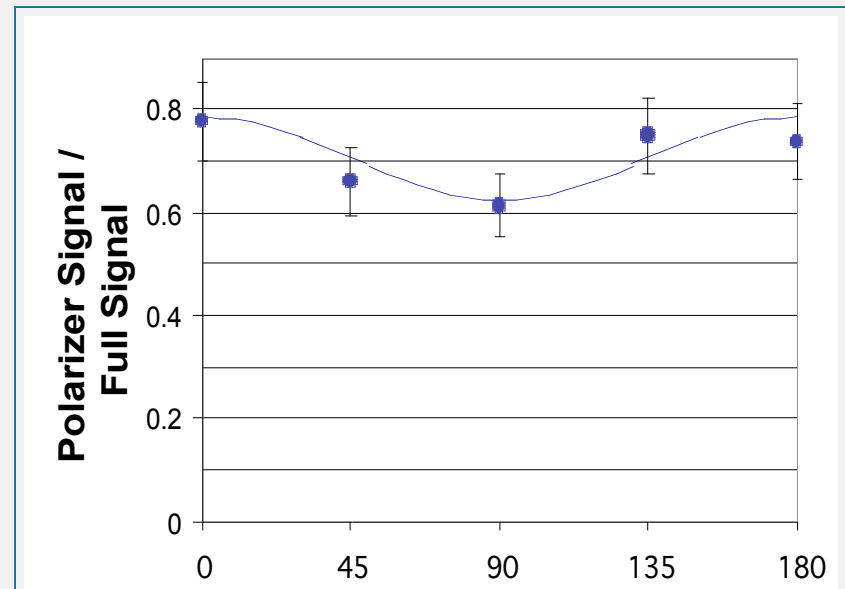
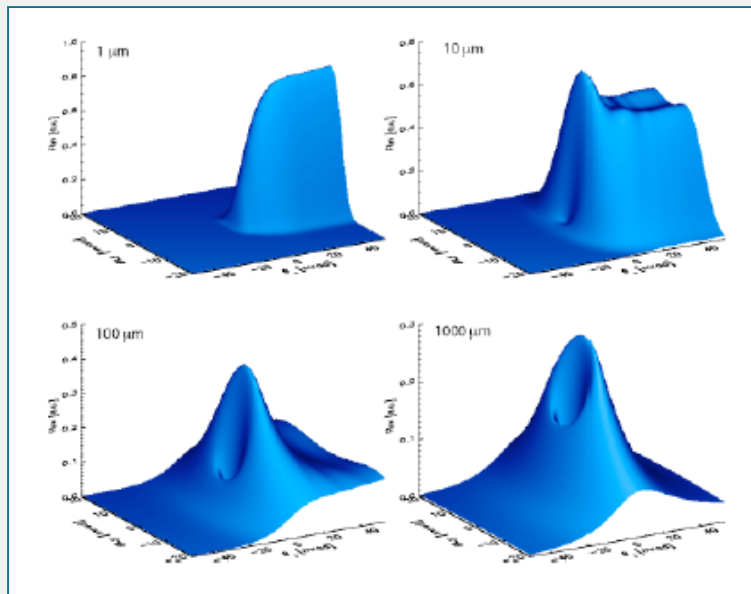
theoretical curve





# CER Polarization

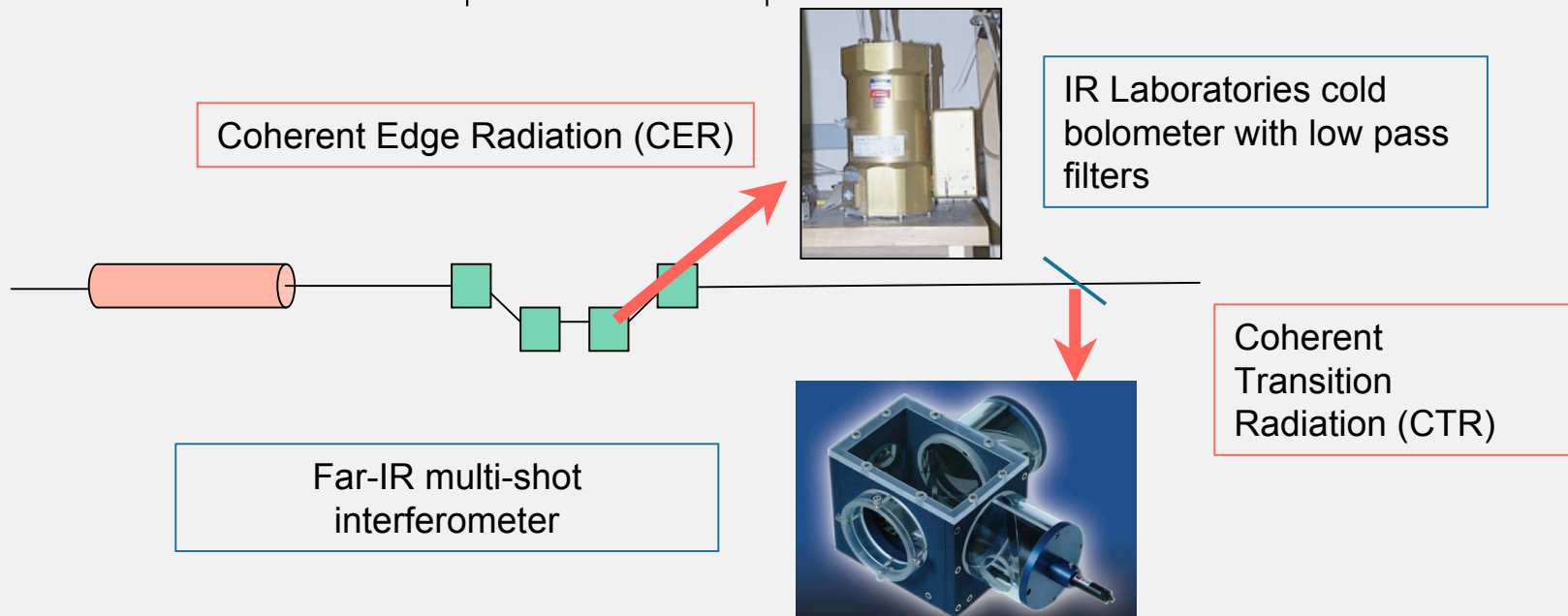
- ✓ CER semi-analytical model by S. Reiche:
  - Asymmetric at short wavelength
  - Symmetric at long wavelength
- ✓ Polarization measurement shows slight ellipticity



# Coherent Radiation Measurements

For an electron beam, the radiated spectral intensity depends on the longitudinal profile of the electron beam:

$$\mathcal{E}(\omega) \approx \mathcal{E}_0(\omega) N_e^2 \left| \frac{1}{Q} \int_{-\infty}^{\infty} I(t) e^{i\omega t} dt \right|^2 \sim \mathcal{E}_0(\omega) |\tilde{I}(\omega)|^2$$



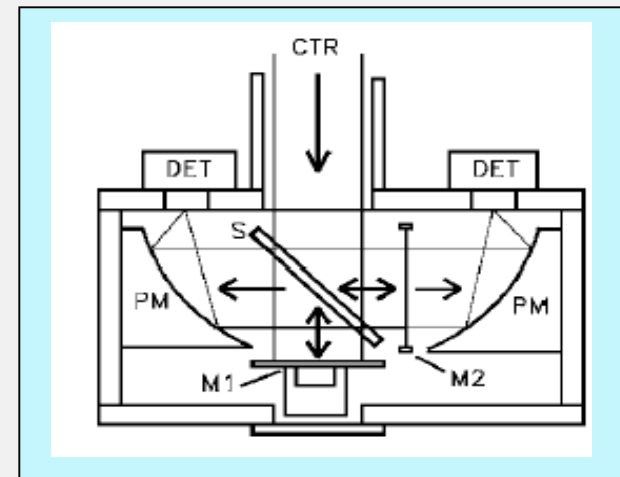
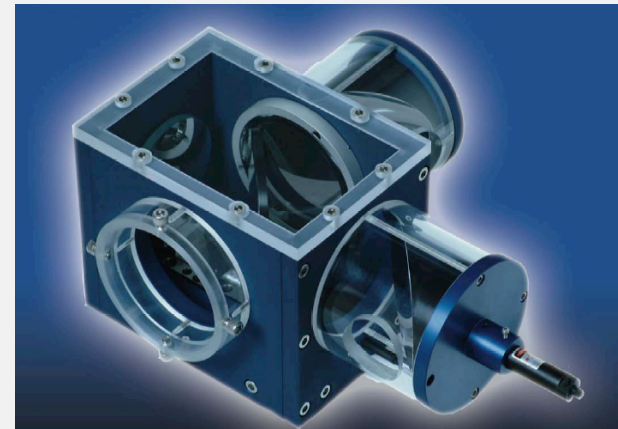
# CTR Interferometer

## ✓ Michelson Interferometer

- Commercial product by RadiaBeam Technologies (licensed from U. Happek group at U. Georgia)
- Convenient alignment
- Beamsplitters range: 10  $\mu\text{m}$  - 1 mm (tested)
- Step size: 0.6  $\mu\text{m}$

- ✓ Changing one arm of the interferometer allows to measure the autocorrelation of the CTR signal:

$$S(\tau) \sim \int I(t)I(t + \tau)dt$$



# Golay Cell Detectors

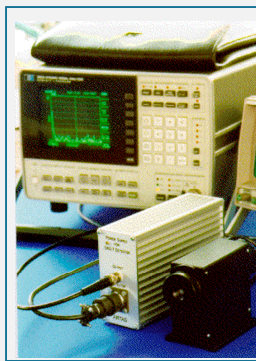
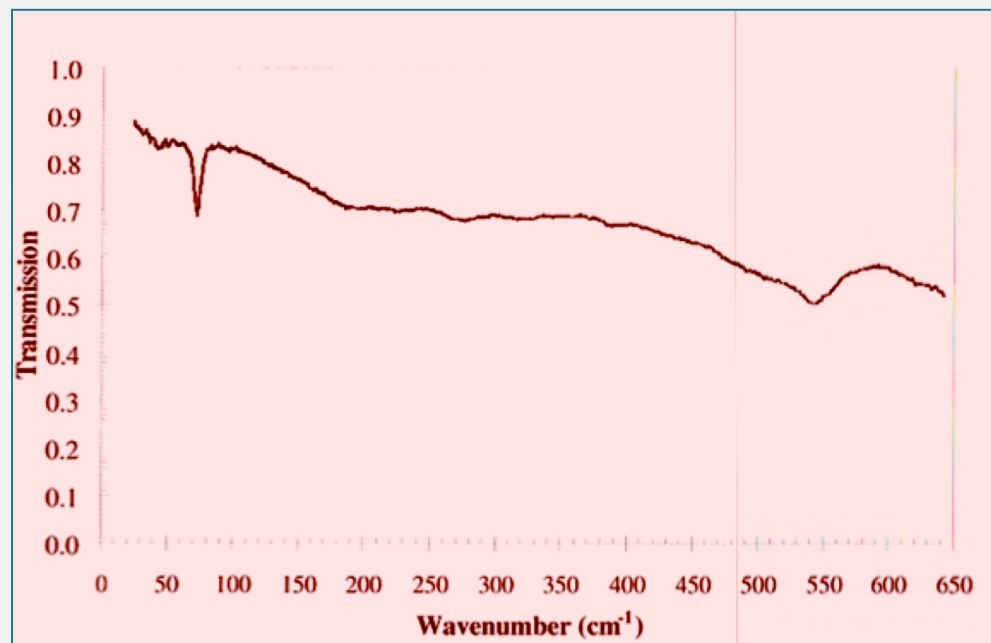
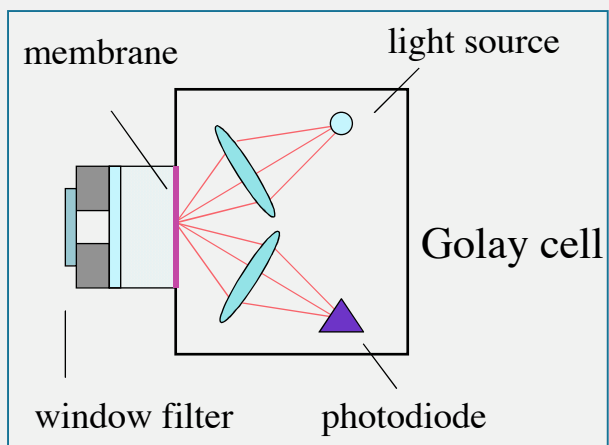


Photo-acoustic detector



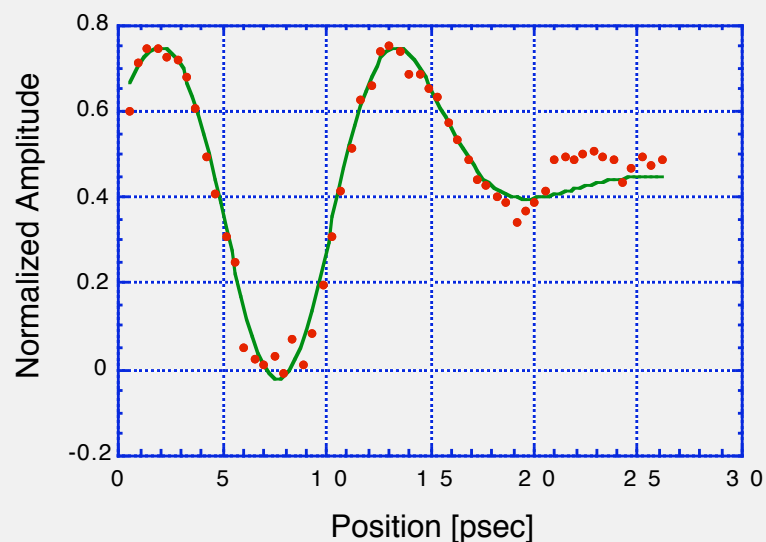
HDPE filter transmission curve

# Data Analysis

Fourier transform measured autocorrelation function:

$$\tilde{S}(\omega) \sim |\tilde{I}(\omega)|^2 k_{\text{LOSSES}}(\omega)$$

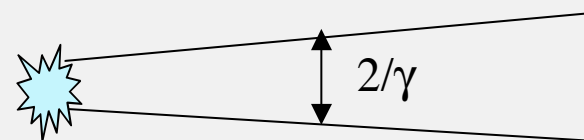
$$k_{\text{LOSSES}}(\omega) = 1 - e^{-\omega^2 \xi^2}$$



Missing long frequencies due to:

- Goly Cell window acceptance
- Beamsplitter Efficiency Losses
- Radiator size

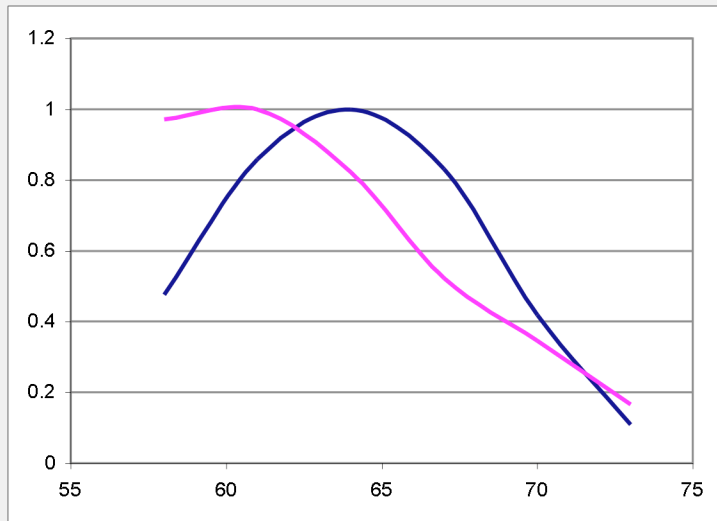
$$2\pi\sigma_{\text{eff}} \sim \gamma\lambda/2$$



For the ATF beam the problems appear at  $\lambda \sim 300 \mu\text{m}$   
 $(\gamma \sim 140 \Rightarrow 2\pi\sigma_{\text{eff}} \sim 2.1 \text{ cm})$

$$S(\tau) \sim \left[ e^{-\frac{\tau^2}{4\sigma_t^2}} - \frac{2\sigma_t}{\sqrt{\sigma_t^2 + \xi^2}} e^{-\frac{\tau^2}{4(\sigma_t^2 + \xi^2)}} + \frac{2\sigma_t}{\sqrt{\sigma_t^2 + 2\xi^2}} e^{-\frac{\tau^2}{4(\sigma_t^2 + 2\xi^2)}} \right]$$

# CTR Data

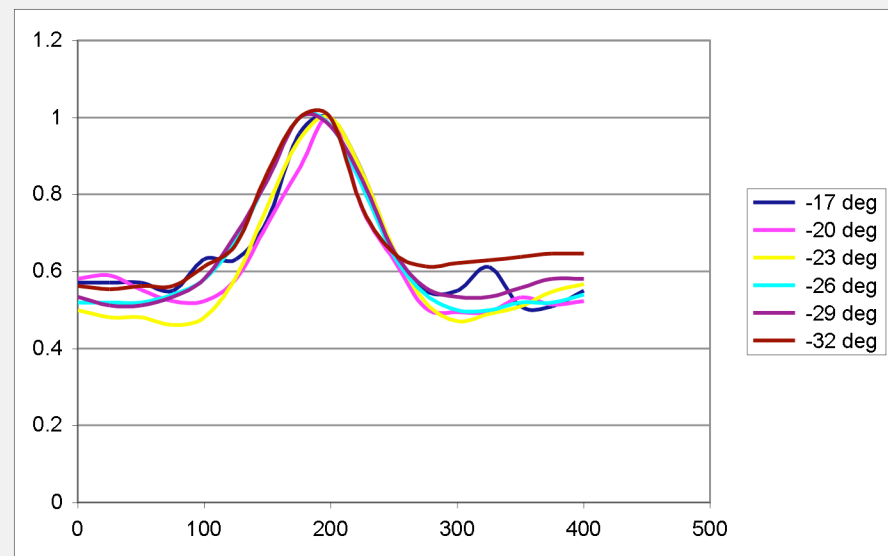


## ✓ CTR Amplitude

- strong dependence on compression intensity
- Phase dependence of CTR signal slightly differs from CER data

## ✓ CTR Autocorrelation width

- weak dependence on compression intensity
- phase curvature effect?



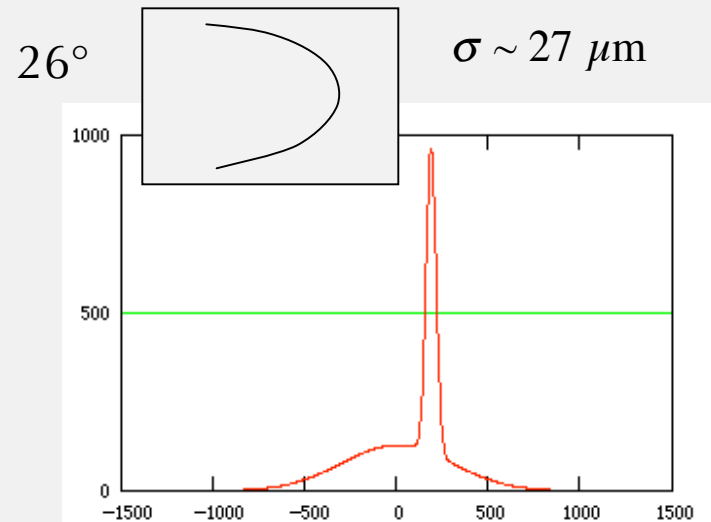
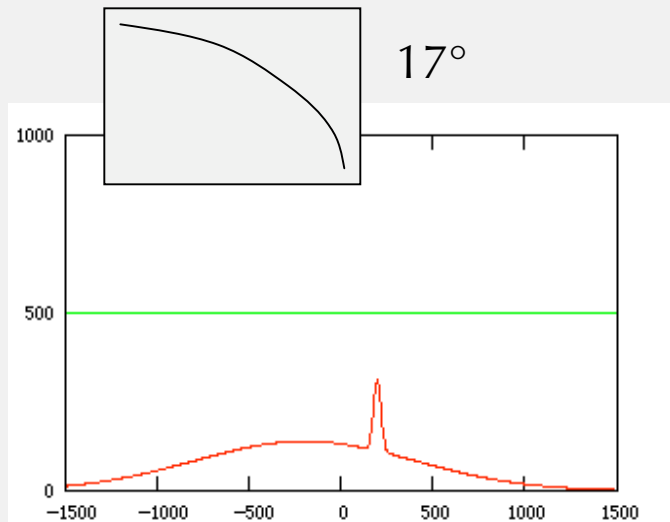
# Data Decomposition

Bi-Gaussian current model: 
$$I(z) = I_0 \left( e^{-\frac{(z-z_1)^2}{2\sigma_1^2}} + \delta e^{-\frac{(z-z_2)^2}{2\sigma_2^2}} \right)$$

low pass filter 
$$f(k) = 1 - e^{-\frac{k^2 \xi^2}{2}}$$

$$I_s(z) = I_0 \left( e^{-\frac{(z-z_1)^2}{2\sigma_1^2}} + \delta e^{-\frac{(z-z_2)^2}{2\sigma_2^2}} - \frac{\sigma_1}{\sqrt{\sigma_1^2 + \xi^2}} e^{-\frac{(z-z_1)^2}{2(\sigma_1^2 + \xi^2)}} - \delta \frac{\sigma_2}{\sqrt{\sigma_2^2 + \xi^2}} e^{-\frac{(z-z_2)^2}{2(\sigma_2^2 + \xi^2)}} \right)$$

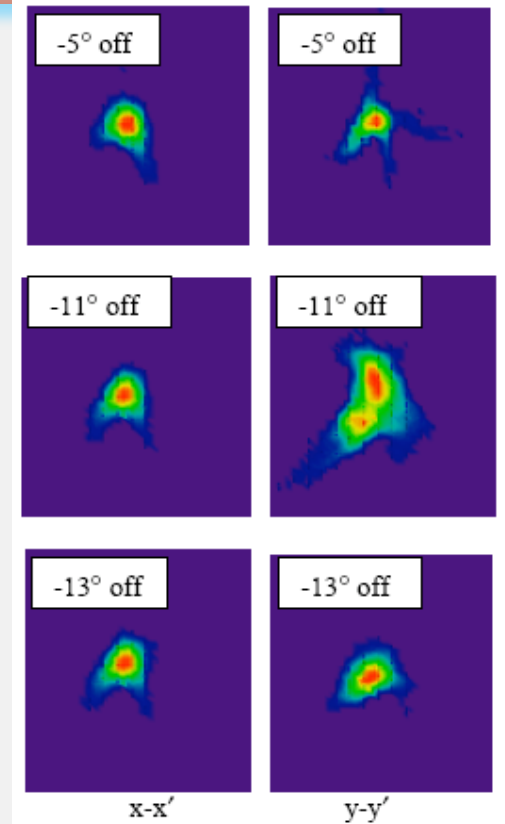
$$A(s) = \int I_s(z-s) I_s(z) dz$$



# Transverse Effects

- ✓ Tomography
  - Quadrupole scanning tomography developed at ATF
- ✓ Operating parameters
  - Energy = 60 MeV
  - Charge = 200 pC
- ✓ Mild bifurcation observed
  - Space charge forces giving phase space bifurcation are alleviated at this energy

F. Zhou *et al.*, Experimental Characterization of 4-D Transverse Phase Space of a Compressed Beam, PAC 2005 Proceedings



Bend plane is along vertical axis.  
Reconstructed phase space plots for under-, full-, and over- compression



# Conclusions

## ✓ Summary

- Chicane compressor installed and commissioned
- Compressor provides a rich data set
  - ♣ *CTR, CER, momentum spread, tomography*
- Simulations need to catch up
  - ♣ *Microscopic physics model*

## ✓ Future Run Plans

- Understand CER filter measurements
- Obtain more CTR data and develop analysis scheme for non-symmetric beam
- Compare data to models (Field-Eye)